

## **Performance of Passive and Active Sonars in the Philippine Sea**

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### **LONG-TERM GOALS**

We have the long term goals of understanding several aspects of passive and active sonar performance in the Philippine Sea when there is a robust environmental characterization of the sea floor and water column plus accurate source/receiver positions.

### **OBJECTIVES**

The objectives this year have been to model the features of a CZ which we observed in the PhilSea09 experiment. The data from this found very abrupt transitions and into the CZ's and narrow widths for them. We note that not all CZ's "focus", *i.e.* sharp edges as we observed in the Philippine Sea. This feature has been noted by Brekhovskikh and Munk where they noted that such zones tend to remain clustered for many CZ's. (3),(5) We are also concerned with the width of the transitions as well as the stability of signals once a receiver is within a CZ. These factors have significant implications for source localization at CZ ranges.

The CZ is one of the most notable features of deep ocean sound propagation. Several models for the sound speed profile have been used to model the propagation. (5), (6), (7) The cycle distance has been studied extensively. The width has been studied in (7) using rays bounded by bottom interaction and a mixed layer near the surface. However, the sharpness of the edge has not been examined. Efforts last year measured the characteristics of the convergence zone (CZ) and this year we have started to model the edge sharpness and width.

The Philippine Sea experiments for acoustics and signal processing were executed in two separate cruises in April-May 2009 and in July 2011. There were many source-receiver configurations over the time of the experiment. In 2009 multichannel data were recorded on the FORA (Five octave research array) HLA (horizontal line array) towed by the *R/V Kilo Moana* and the DVLA (Deep Vertical Line Array) moored VLA (vertical line array). Narrowband tones and broadband LFM (linear frequency modulated) chirps were transmitted by a shallow (60 m) J-15/3 at a level of  $\sim 172 \text{ dB re } 1 \mu\text{Pa} @ 1 \text{ m}$  and M-sequences by a deep (1000 m) University of Washington MultiPort-200 at a level of  $195 \text{ dB re } 1 \mu\text{Pa} @ 1 \text{ m}$  both from the *R/V Melville*; LFM's were also transmitted from a Webb WRC source moored at 1000 m at a level of  $190 \text{ dB re } 1 \mu\text{Pa} @ 1 \text{ m}$ . In 2011 data were recorded on a water

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column spanning DVLA from LFM signals transmitted by a shallow J-15/3 towed by the *R/V Revelle* and by five Webb WRC sources moored at 1000 *m*. This was done for many ranges and azimuth tracks from the DVLA.

The results discussed here concern the J-15/3 transmissions to the FORA in 2009. The transmissions to the FORA from the Webb WRC and MP200 as well as the 2011 transmissions to the DVLA are now being analyzed. Unfortunately, there were some equipment problems with the FORA, so travel time analyses have been compromised. Also, weather events (nascent typhoon) led to a premature end of the experiment.

## APPROACH

The multichannel array data acquired on the FORA and DVLA were very extensive which have required time intensive signal processing. We have concentrated on the active, broadband processing across and within CZ's since we could obtain differential travel times as well as distance when supplemented by GPS. The signal processing is done by beamforming on the source using both conventional and adaptive methods and then match filtering, or pulse compressing, the LFM. This leads to a peak at the azimuth and range to the LFM source signal. Two features of the performance have been examined: i) The transmissions across a CZ's and ii) the signal coherence while within a CZ. These features were measured by running i) a "STAR" pattern which crossed the CZ's in range yet put the azimuth beam at aft endfire quarter so as to mitigate tow ship self noise and ii) then by running at a constant range using GPS with the FORA at broadside.

These features are motivated by the following observations: i) The transition across a CZ boundary is often very abrupt so knowledge of the sound speed profile and receiver depth and array orientation do permit "CZ localization". Range and bearing can be inferred. With an understanding the relative travel time of the paths, potentially depth might be estimated as well. While the concept of CZ localization or ranging is not new, the implementation requires understanding the CZ interference as a function of the source and channel parameters. (2), (8) Accurate estimates require a sharp boundary as well as assumptions about the source depth. This SVP leads to especially abrupt CZ edges. The CZ signal is well modeled by four paths from the source: the product four combinations of direct and surface reflections at the source and receiver. The J15/3 source depth was at either 15 *m* or 60 *m* while the FORA tow depth was nominally 240 *m*, so these paths group into two arrival packets according to the source depth. Since we were using wideband signals which resolve travel time, the FORA observes two CZ rings corresponding to the two direct and locally surface reflected paths. For the sound speed profile present the rings were consistently from 58.9 – 60.2 *km* and 63.3 – 65.8 *km* or  $\approx 1.3$  and 2.5 *km* respectively. (The FORA is only 192 *m* long, so its length does not blur these measurements and the effective range rate of the FORA led to a spatial sampling of less than 200 *m* at the 180 *s* PRI.)

## WORK COMPLETED

We have concentrated on the data from the 2009. We have examined the 2011 data to make sure it contained our signals of interest; however, we have not had the time to process much of it. The data in the '09 have been simply too large and filled with some annoying data acquisition issues which have consumed a lot of time. We have implemented beamforming, pulse compression and frequency azimuth (FRAZ) software plus several "peak picking" algorithms often associated with tracking for active sonar

signal processing. We have concentrated on the first "STAR" pattern and the constant "CZ offset" tracks. Transmissions to the DVLA and from the T1 source has been initiated. The results are a bit different as much of the data were at multiple CZ's leading to a quite different signal structure because of multipath. As an aside, we note that our preliminary measurements suggest strong coherence among the multipaths which suggests that multiple CZ matched field processing (MFP) would be successful consistent with earlier experiments in long range, deep water MFP. (1) We have also applied the beamforming and FRAZ processing for ambient noise analysis; however, this is not presented here because of space and the many options for processing noise data.

We have concentrated on modeling the CZ transits. Almost all the literature we have examined concentrates on narrowband tonals or a collection of tonal. While there has been considerable use of broadband signals such as for active sonar and ocean acoustic tomography, there seems to be a paucity of material on the signal amplitude of CZ transitions or the coherence of among multiple transmissions while within a CZ. Future efforts will be on a theoretical basis for our observations to match the numerical parabolic equation modeling.

## RESULTS

### CZ Transits - experimental data

Figure 1 is a 2 1/2 D parabolic equation (PE) model for the transmission loss TL from the J15/3 at location SS45. The black line is a super-imposition of the track of the FORA for part of the "STAR" pattern ran to intersect the CZ. The double ring caused the CZ are evident. Note also the very sharp transitions into the CZ. The combination of this sound speed profile and the source/receiver depths imply a very accurate parameter estimation of the range which can be combined with a bearing estimate. This implies a localization within  $\approx 1.3 \text{ km}$  in range and  $2.0 \text{ km}$  cross range. There are also indications of "bottom bounce" returns at ranges closer than the CZ and "multiple" ones at ranges farther.

The "zig-zag" black trace superimposed on the TL indicates part of the star pattern of the track of the *R/V Kilo Moana*. For this discussion we are interested starting on the first leg on the point of the star pattern just after exiting the second ring of the CZ at  $65 \text{ kms}$ . Figure 2 illustrates the receptions for the two LFM bands transmitted by the J15/3 with the source-receiver beneath. The vertical lines indicate the transition of the first CZ edge. The beam outputs were "peak picked" as the reception angle changed during each leg of the star. We note i) the width of each of the CZ bands is very narrow as suggested by the modeling of in Figure 1; ii) the transition into and out of the CZ band is very abrupt (the receptions are aliased "graphically" by the density of the plotting; and iii) the regions in between the CZ when the *R/V Kilo Moana* was closer than the first CZ edge at  $59 \text{ km}$  is filled with bottom bounce returns. Our goal is to understand the transitions and width of the CZ using the full field Oasis code as well state of the art array processing methods for wavenumber transient field.

### CZ Transits - modeling

We have used a series of perturbations of the Munk sound speed profile. These are illustrated in Figure 4. They should be read in the sequence: MUNKE, MUNKA, MUNKB, MUNKC then MUNKD. This order corresponds to the deepest axis for MUNKE to the shallowest at MUNKD. In the literature CZ's are usually displayed as combination of acoustic paths. For such there is the quartet created by the surface reflection near the source and receiver. In addition, often bottom bounce, or near grazing, paths are included. To improve our understanding we simplify the analysis by identifying the "direct" CZ

bath by suppressing surface and bottom reflections at the the source and receiver. We have extended the bottom well below the excess depth so there is only refracted energy at the CZ. The surface reflected signals have also been suppressed by replacing the free surface with one no reflections, *i.e.* no acoustic impedance contrast. These modifications enable examination of just the refraction issues with the CZ propagation since at time it is almost impossible to separate the interference patterns.

Figure 5 examines how two of the CZ properties are modulated as a function of the profile used and the receiver depth for a source at 60 m. (We have placed receiver depth on the vertical axis since this is usually displayed as such. Also note that the depth scale is Figure 5 is a very expanded scale compared to Figure 4.) On the left is an estimate of how abrupt the CZ is. This is done by fitting the pressure dependence as a function of range at the receiver depth, so the units are Pascals per kilometer ( $10^{-2}\mu Pa/m$  for a 0 dB source. We observe that with the exception of MUNKE all the other profiles lead to the maximum sensitivity when the receiver is near the source depth. At depth the gradient steps from the least sensitive for MUNKE to the most for MUNKD with the outlier MUNKD in the middle. There appears to be a threshold starting with MUNKD which has the least sensitivity as a function of depth.

The right side of Figure 5 indicates the CZ width for each of the profiles. Thw width has been estimated by the points where the level first exceeds a threshold and the when it falls below the same threshold. Here, there is a progression from MUNKE to MUNKD for the width at all depths. We note that range to the CZ also decreases with these profiles. MUNKD is similar to models with Arctic profiles with a spread of refracted signal, but here there is narrow extent where signals refracted above the receiver can be present. The widths for these models are much larger than observed experimentally, so the threshold crossing has probably been set too low.

This modeling has been done by a GRA working with Prof. Schmidt. We now intend to use signals of finite bandwidth and apply short time wavenumber processing similar to velocity analysis done for seismic propagation. These approaches should lead to better path identification. We are also introducing the Airy functions needed to model signal undergoing total internal reflection which hopefully leads to an understanding if the gradients and widths.

## IMPACT/APPLICATIONS

There are two potential applications: 1) The very sharp edge of the CZ's at this location in the Philippine Sea could be exploited for accurate source localization. 2) The coherence over very wide extent of CZ receptions suggests an opportunity for synthetic aperture methods for better detection and localization of CZ sources.

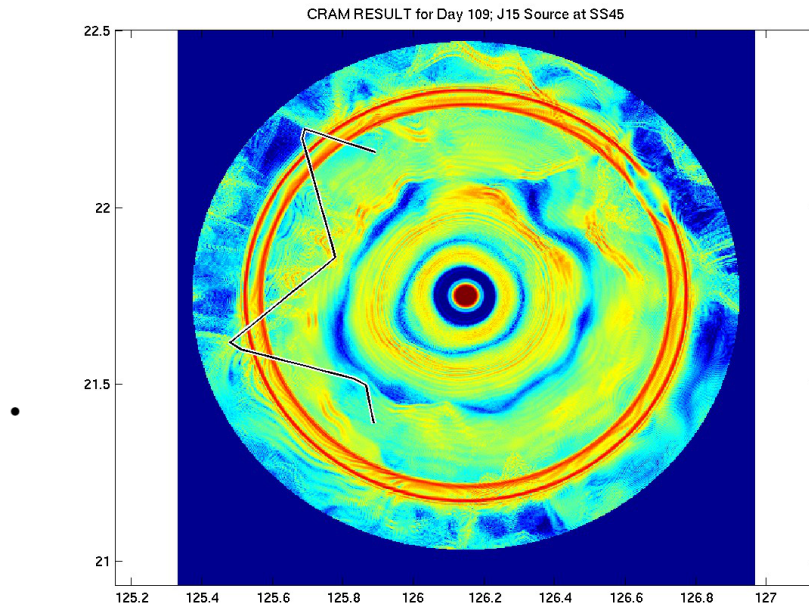
## REFERENCES

- [1] Baggeroer, A. B., Kuperman, W. A. and Schmidt, H., "Matched field processing: source localization in correlated noise as an optimum parameter estimation problem", *Journal of Ocean Engineering*, vol. 83, [1988]
- [2] Beilis, A., "Convergence zone positions vis ray-mode theory", *J. of the Acoustical Soc. of America*, vol. 74(1), pp. 171 - 181, [July 1983]
- [3] Brekhovskikh, L. and Lysanov, Y., *Fundamentals of Ocean Acoustics, 3rd Edition*, pp. 58-60, Springer, New York, [2001]
- [8] Galkin, O.P., Kharachennko, E. A. and Shvachko, L. V., "Acoustic field structure in the first oceanic convergence zone for different frequencies in the audio range", *Acoustical Physics*, vol. 46(3), pp. 274 - 283, [2000]
- [5] Munk, W.H., "Sound channel in an exponentially stratified ocean with applications to SOFAR", *Journal of the Acoustical Soc. of America*, vol 55, pp. 220 - 226, [1974]
- [6] Miller, J.C., "Oceanic acoustic rays in the deep six sound channel", *Journal of the Acoustical Soc. of America*, vol 71, pp. 859 - 862, [1982]
- [7] Bongiovanni, K.P. and Seigmann, W.L., "Convergence zone feature dependence on ocean temperature structure", *Journal of the Acoustical Soc. of America*, vol 100(5), pp. 3063 - 3041, [1996]
- [8] Galkin, O.P., Kharachennko, E. A. and Shvachko, L. V., "Acoustic field structure in the first oceanic convergence zone for different frequencies in the audio range", *Acoustical Physics*, vol. 46(3), pp. 274 - 283, [2000]

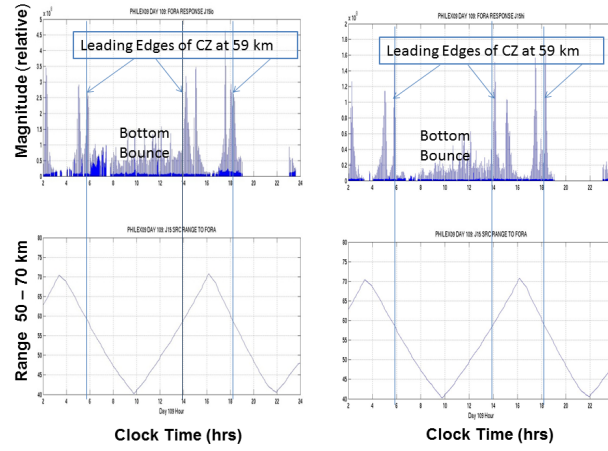
## RELATED PROJECTS

1. Vector Sensor Array Signal Processing  
N00014-07-12-0050
2. WHOI MURI on acoustic communications
3. SECNAV/CNO Chair "white paper" on recommendations to the CNR for an ONR Arctic acoustics program
4. SSTAG (Submarine Surveillance Technical Advisory Group) for N975)
5. FCP (Future Concepts Program for Design for Undersea Warfare) for COMSUBFOR)

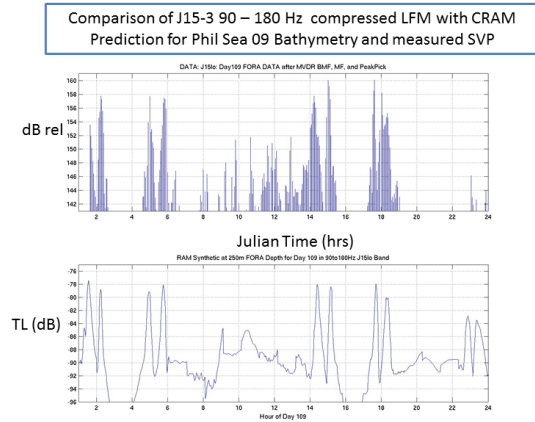
## FIGURES



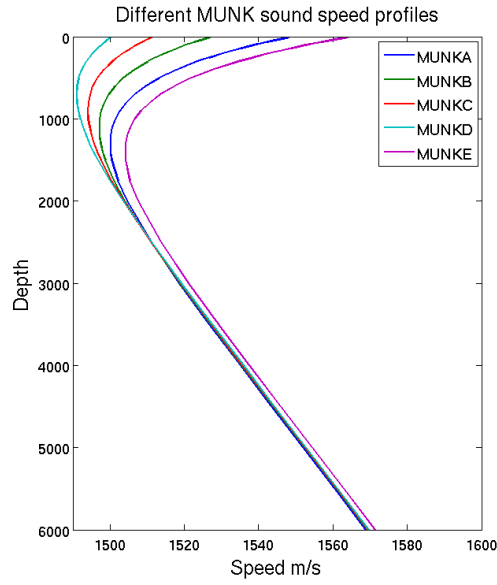
*Figure 1: C-RAM (C-RAM) 2 1/2 modeling broadband incoherent TL transmissions from the R/V Melville to the FORA running part of a "STAR" pattern indicated by the black line segments . The source depth was 60 m and the FORA was towed at 240 m. The two CZ rings corresponding to the direct and the surface reflection near the FORA. Inside the CZ rings "shadow zones" (deep blue) and "bottom bounce" returns are evident. (C-RAM courtesy K. Heaney)*



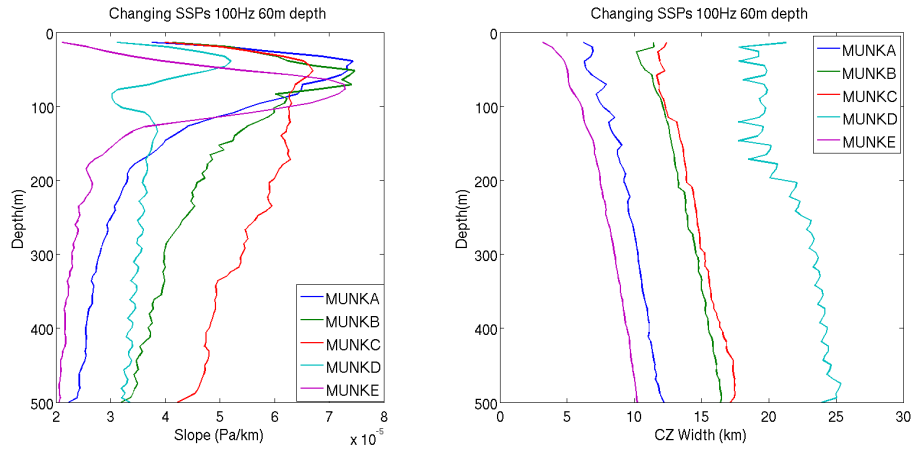
**Figure 2: Levels in dB vs. range for low (left) and high (right) compressed LFM signals. Top is the peak picked outputs. Bottom is range. The transmissions start as the FORA crosses away from the 2nd CZ ring at 66 kms on the first star point. Vertical lines are 1st CZ interior edge positions.**



**Figure 3: Comparison of experimental low band pulse compressed signal and CRAM prediction. The Julian Time has been mapped to the range as indicated in Figure 2.**



**Figure 4: Five SVP's based on the Munk model for comparing CZ features. The sequence should be read from MUNKE which has the deepest axis to MUNKD which has the shallowest.**



**Figure 5: Comparison of CZ features for the Munk profiles. The left is the gradient in Pa/m for the leading edge of the CZ. The right is the width of the CZ.**